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Energy level diagram of X^- in high magnetic fields

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Abstract. We have studied the photoluminescence energy of the negatively charged exciton in a 100 Å GaAs/AlGaAs quantum well using magnetic fields up to 50 T. By observing recombination from all of the optically active singlet and triplet states of the charged exciton, we have determined its energy level diagram.

Introduction

The recombination spectra of semiconductors are dominated by excitons. A neutral exciton X_0 consists of a hole bound to an electron by the Coulomb interaction. If X_0 binds a second electron, then we have a negatively-charged exciton X^-, or trion. The neutral exciton is the solid-state analog of the hydrogen atom H, while X^- is the analog of the negatively-charged hydrogen ion H^-. Since X^- is a three-body system, its physics is more complicated than the X_0. Indeed, X^- is currently the subject of much theoretical [1] and experimental [2–4] investigation. Here we present photoluminescence (PL) experiments in magnetic fields, B, up to 50 T on a 100 Å GaAs QW. We have measured all the experimentally observable transitions of the singlet and triplet states of X^-, and so reconstructed the level diagram.

1. Experimental details

The 100 Å GaAs/AlGaAs QW sample was grown by molecular beam epitaxy. Our experiments were undertaken at 1.2 K with B parallel to the growth direction of the QW. Photon counting times between 0.4 ms and 2 ms during the 25 ms field pulse resulted in a field resolution of $\pm 1\%$ and $\pm 3\%$. The spectral resolution was better than 0.5 meV. A solid-state laser (wavelength 532 nm) was used to excite the sample and reduce the electron density in the QW. Optical access to the sample was provided by a fibre bundle. An *in-situ* polariser was used in combination with reversing the field direction to distinguish between the right- (σ^+) and left-handed (σ^-) circularly polarised light.

2. Experimental results

Figure 1 shows the energy of the excitonic recombination as a function of B. The four lines, labelled as S_1, S_2, T_1 and T_2, are due to the luminescence of the different states of X^-. The open and closed symbols present σ^+ and σ^- respectively. At low fields ($B < 10$ T) we observe a splitting between S_1 and S_2 with polarisation σ^- and σ^+. A third line, T_1, appears at $B = 4.2$ T and is the highest energy line at these low fields. At higher fields ($B > 10$ T) the recombination energy of T_1 and S_2 is the same between 14 T and 26 T. However, we can distinguish the different lines via the polarisation which is positive for S_2 and negative for T_1. Above 26 T, T_1 becomes lower in energy than S_2 and parallel with S_1.

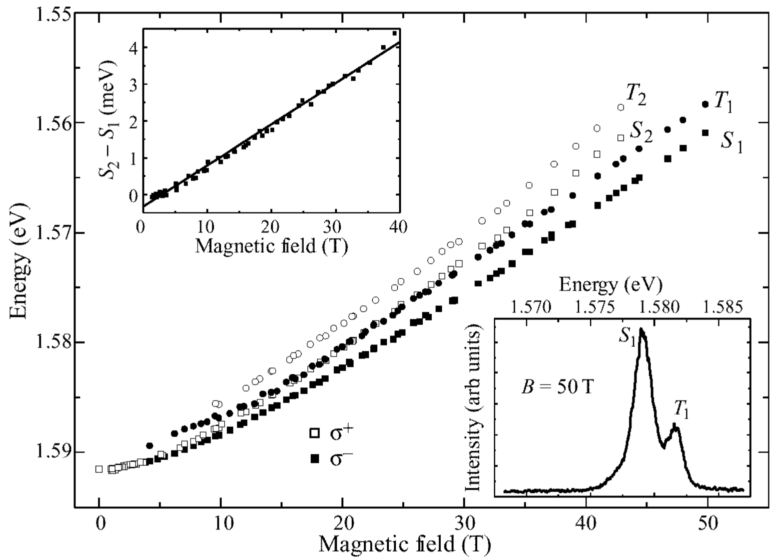

Fig. 1. Field dependence of the PL peak energy. The upper inset shows the difference between S_2 and S_1, which is identified as the spin splitting of the singlet state. The lower inset shows a spectrum at $B = 50$ T with σ^-.

The fourth excitonic line, T_2, appears at 10 T and is the highest PL energy for fields up to 43 T. The intensity of S_2 and T_2 decreases above 4 T, and these lines disappear at 43 T. T_1 and S_1 remain visible at all fields.

3. Discussion

We use our experimental data to construct an energy diagram for the X^-. We start by considering the two electrons, which must have an antisymmetrical total wave function. One possibility is by an antisymmetrical spin wave function and a symmetrical spatial wave function, which we refer to as the singlet state. One can also make three combinations of a symmetrical spin wave function and an anti-symmetrical spatial wave function to get the triplet state. If we then include the hole, every level splits into two sublevels with a total z component of the spin S_z. The degeneracy of the splitting is lifted by the Zeeman interaction. A schematic diagram showing the previously used level stucture for the X^- is shown in the inset of Fig. 2 [2]. Our experimental results have shown that because the splitting of these levels is sensitive to the electron and hole gyromagnetic ratio (g_e and g_h respectively), it is necessary to redraw the energy level diagram as shown in Fig. 2.

We first start with the two possible singlet transitions 1 and 2, which have a different polarisation, σ^- and σ^+ respectively. These transitions (corresponding to S_1 and S_2 in Fig. 1) are the lowest in energy at low fields, as can be found in the literature [2]. When taking the difference in PL energy between S_1 and S_2 of our data, we observe a linear behaviour as a function of field (inset Fig. 1), with a slope of 0.11 meV/T. Using the equation for the Zeeman splitting of the PL

$$\Delta E = (g_e + 3g_h)\mu_B B, \quad (1)$$

where μ_B is the Bohr-magneton and $g_e = -0.2$ [5], we find that $g_h = 0.7$. This value is consistent with that found by Snelling for the exciton in a 100 Å QW [5, 6]. Notice that

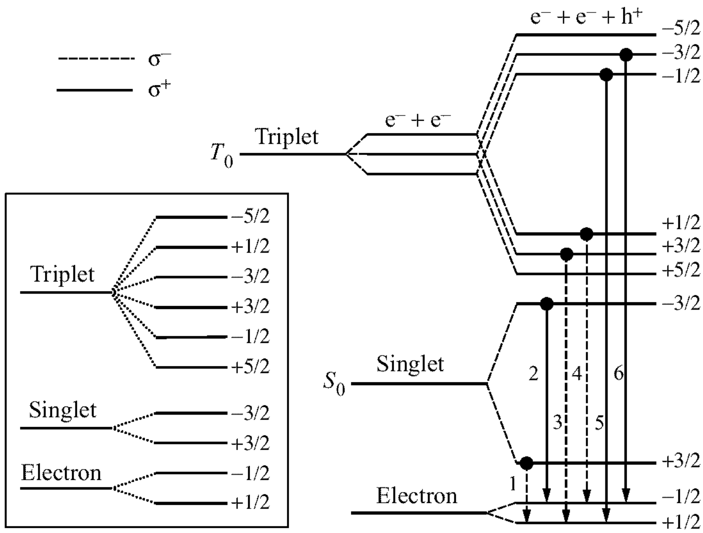

Fig. 2. Schematic energy level diagram of the different states of X^- for $g_e < 0$ and $g_h > 0$. The photon changes the total z component of the spin (S_z) by $+1$ and -1 for the positively polarised light σ^+ and negatively polarised light σ^- respectively. The inset shows the diagram without taking into account the different g factors.

because the total electron spin is zero in the singlet, this splitting is only caused by the hole. For the triplet states, there are four optically allowed transitions, two σ^- (transitions 3 and 4) and two σ^+ (transitions 5 and 6). Transitions 3 and 4 have the same PL energy, while they connect different energy levels. The same is true for transitions 5 and 6. This means we cannot make a distinction between transitions 3 and 4 (5 and 6) optically. The levels triplet($-5/2$) and triplet($+5/2$) are optically dark. We identify transitions 3 and 5 with T_1 and T_2 respectively in our experimental data in Fig. 1. The Zeeman splitting for the triplet is not as straightforward as for the singlet, and needs more explanation. For a start, the triplet is not bound at low fields [1–2]. Above 25 T, the difference between T_1 and T_2 is linear in field with the same slope as the singlet. This is to be expected from the level structure in Fig. 2. The linearity becomes very bad at fields between 16 T and 25 T, where we observe T_1 to have the same PL energy as the positive component of the singlet, S_2. We do not believe that the absence of a clear crossing has any physical significance, and attribute it to a lack of resolution in the data. At the field where the singlet($-3/2$) and triplet($+3/2$) coincide, the spin splitting of the singlet state must be equal to the separation of the triplet and singlet states in the absence of spin (T_0 and S_0 in Fig. 2). We can use this level coincidence to determine the hole g factors as we did with the singlet splitting. We find $T_0 - S_0$ to be constant in field and equal to 2.2 ± 0.3 meV. Locating the midpoint of the crossing between T_1 and S_2 at B_0=20 T, we can construct the following equation

$$(g_e + 3g_h)\mu_B B_0 = T_0 - S_0. \tag{2}$$

This gives us $g_h = 0.7$ using $g_e = -0.2$. This calculation gives essentially the same value for g_h quoted in the literature [5], thereby confirming the revised energy level diagram of Fig. 2. Although level triplet($+5/2$) is optically dark, it becomes the ground state at very high fields. This is the case when it is lower in energy than singlet($+3/2$) which, if

we assume $T_0 - S_0$ remains constant, is at about 190 T. This field was predicted by theory to be 30 T [1]. Finally, we note that, in contrast to other studies [2, 4], we do not observe the neutral exciton, except at fields below 15 T, where it is expected to merge with T_1. Indeed, we can confirm our assignment of T_2 as the triplet($-3/2$) from the polarisation, which should be σ^- for the lowest energy splitting for X_0 [4]. We believe that the lack of X_0 recombination is due to an excessive electron density in the QW.

4. Conclusion

We have studied the PL of the singlet and triplet states of X^- in a 100 Å GaAs QW. Although we do not observe X_0, we are able to determine all possible transitions of the singlet as well as the triplet state. This allows us to construct an energy level diagram for X^-. The value of the hole g factor we determine for the X^- is the same as that for the X_0 in the literature.

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